SC DC-3131

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5/31 1963

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IMPLICATIONS OF EXPERIMENTAL DATA ON THE SCALING OF CRATER DIMENSIONS

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IMPLICATIONS OF EXPERIMENTAL DATA ON THE SCALING OF CRATER DIMENSIONS

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This paper reviews four current methods of scaling crater dimensions, none of which is universally applicable, and evaluates them in the light of available experimental information. The adequacy and the inadequacy of each of the methods is discussed. Had all the experiments been carried out in a single medium, the evaluation would be considerably simplified. Experimental results have indicated (Reference 1) that differences in material strength properties decrease in importance as the charge weight is increased, and differences in density increase.

SCALING METHODS

Four methods of scaling the linear dimensions of craters have been considered at various times: cube root of charge weight, 1/3.4-power of charge weight, fourth root of charge weight, and overburden approximate scaling. They can best be discussed in the light of experimental data from Nevada Test Site (NTS) desert alluvium.

Cube-Root Scaling -- Dimensional analysis predicts that the linear dimensions of craters will scale as the cube root of charge weight if gravity effects are disregarded, and cratering experiments with small charges (Reference 2) appeared to substantiate this prediction. Cube-root scaling was therefore the predominant scaling method until 1960 when experiments began to verify those earlier suspected departures from cube-root scaling which would be expected if gravity effects were not ignored.

<u>1/3.4-power Scaling</u> -- Experiments conducted before 1960 (References 3, 4, 5) used charges as large as 256 pounds over a range of burst depths, as well as several 2560-pound charges and one 40,000-pound charge at relatively shallow burst depths. These experiments showed no significant departures from cube-root scaling. Project Stagecoach (Reference 6) furnished the first information which reliably substantiated the suspected departure from cube-root scaling. An earlier evaluation of craters from 256-pound charges at the Nevada Test Site had led Vaile (Reference 7) to suggest that crater dimensions would scale as about 1/3.4-power of the charge weight or yield. The information from Project Stagecoach together with that obtained later from Project Scooter enabled Chabai (Reference 8) and Nordyke (References 9, 10) to arrive independently at 3/10-power scaling and 1/3.4-power scaling, respectively.

Figure 1 shows crater radius versus charge weight, and Figure 2 gives similar information for crater depth as a function of charge weight; both show that 1/3.4-power scaling rather accurately describes the linear dimensions of craters from charges up to and including 1,000,000 pounds buried at or near depths which maximized crater dimensions.

These Figures also show the data point for Project Sedan. The fact that this value is lower than would be predicted by 1/3.4-power scaling can be interpreted either as an indication that nuclear explosives are less effective than chemical explosives in producing craters from the same energy yield and burst depth or that 1/3.4-power scaling is inadequate beyond one million pounds. There appears to be little prospect of resolving this point until equal-yield nuclear and high-explosive charges have been fired under identical circumstances.

The data of Figures 1 and 2 were obtained by using measured values for Projects Scooter and Sedan, using an extropolated

value to a cube-root-scaled burst depth of 1.25 $ft/lb^{1/3}$ for the two shallowest Stagecoach shots, and using a value for 256-pound charges obtained by interpolating between the average of four shots at 1.0 $ft/lb^{1/3}$ and two shots at 1.5 $ft/lb^{1/3}$.

<u>Fourth-Root Scaling</u> -- Chabai (Reference 6) has suggested, from considerations of the overburden approximate scaling discussed below, that the dimensions of craters from charges over approximately 1 kiloton buried deeper than about 100 feet can be scaled approximately as the fourth root of charge weight. He has shown the relationship of smaller craters from high-explosive charges to larger ones by fourth-root scaling. Fourth-root scaling had earlier been applied to scaling the depth of craters from surface nuclear bursts at the Pacific Proving Ground. (References 11, 12).

<u>Overburden Approximate Scaling</u> -- Chabai and Hankins (References 6, 13) first proposed overburden approximate scaling. This scaling, which is approximate because not all the conditions for similitude are met, takes into account differences in medium density where such differences occur and relates crater dimensions in the following fashion:

$$\frac{R_1}{R_2} = \left(\frac{W_1}{W_2}\right)^{1/3} \left(\frac{DOB_2 + k}{DOB_1 + k}\right)^{1/3} ,$$

where R represents a linear crater dimension, W an energy yield, DOB the burial depth, and k a constant equal to the thickness of the material where its lithostatic pressure equals ambient atmospheric pressure. Overburden approximate scaling is in effect a sliding scale from cube-root scaling for surface bursts or small charges (where the burial depth is zero or very small with respect to k) to fourth-root scaling for very large and deep bursts (where burial depth is very large with respect to k).

The heavy dashed line in Figures 1 and 2 shows that overburden approximate scaling describes well the crater radius or depth over a yield range to and including Sedan within the limits discussed below.

Discussion -- Overburden approximate scaling is attractive especially because it furnishes a means of transition from small-charge crater dimensions to large-charge crater dimensions. Regression analysis (Reference 14) has shown that this scaling agrees with high-explosive experimental data slightly better than 1/3.4-power scaling over a range of charge weights up to and including 1,000,000 pounds.

Figures 1 and 2 illustrate these observations:

(a) Cube-root scaling does not hold for the range of charge weights shown.

(b) 1/3.4-power scaling well describes the HE data, but the values for Sedan are too low. This difference could be attributed to HE-NE (high explosive-nuclear explosive) differences except for the argument presented in the following paragraph.

(c) Fourth-root scaling fits the Scooter-Sedan radius data (suggesting no HE-NE difference), but the Sedan depth appears larger than would be expected (suggesting that HE-NE differences do exist).

(d) Overburden scaling (heavy dashed line in the Figures) describes fairly well the entire range for crater radius, but it too fails to account for the depth of the Sedan crater.

That differences do in fact exist between NE and HE craters cannot be determined conclusively until equal-yield, equal-burst-depth shots of both types have been fired. The best present evidence is from comparison of the Stagecoach II (HE) and Teapot

Ess (NE) shots at the same cube-root scaled* burst depth. Compared to the high-explosive crater, the radius of the nuclear crater was smaller and the depth greater. Thus the greater depth of Sedan is in agreement with this observation, although a smaller radius would have been expected. Note also that an upward revision in the yield used here for Sedan would place radius and depth in the expected relationship with respect to high-explosive results.

Each of the four methods of crater scaling has been applied from the surface up to and beyond the approximate peak of the depth-of-burst curve. Chabai (Reference 6) has suggested that some scaling other than fourth-root might apply to the declining portion of the depth-of-burst curve even in cases in which fourth-root scaling applied to the inclining portion. That the declining portion may scale differently due to a different mechanism being involved is also suggested by the fact that subsidence craters of the Nougat series appear to scale as the cube root of the charge weight or yield (Reference 15). If cube-root scaling defines the declining portion of the depth-of-burst curve, and overburden approximate scaling or 1/3.4-power scaling defines the inclining portion, it is clear that neither of these methods alone can define the peak of the curve over the entire yield range.

A second shortcoming of overburden approximate scaling is the paradoxes which arise in trying to define crater dimensions for surface bursts. This shortcoming, however, is shared by 1/3.4-power scaling, fourth-root scaling, and even cube-root scaling. With overburden approximate scaling, the dimensions

*The validity of a comparison is lessened by the uncertainty of the correct scaling to apply to burst depth.

of craters from surface bursts for all charge sizes should scale as the cube root of the charge weight or yield. Cube-root, fourth-root, or 1/3.4-power scaling apply by implication to surface bursts as well as to those at deeper depths, except that Chabai has limited fourth-root scaling to bursts over 100 feet in depth.

CRATERS FROM SURFACE BURSTS

Let us now examine available information on craters from surface bursts.

Small HE Charges -- The Waterways Experiment Station (WES) examined (References 16 and 17) all available high-explosive cratering data and obtained least-square fits through the data for apparent- and true-crater radius and depth. Table I lists the results of their observations for surface bursts, including soil type, number of observations, and approximate weight range. It should be noted that the paucity of data in a single uniform medium forced WES to combine soils, the characteristics of which may be quite different. Soils for which data were combined and the charge weights involved are listed below, with the numbers in parentheses being number of charges where the number is greater than one.

Item	Soil	Charge Weight (pounds)
(1)	Wet sand	1.29, 256 (2), 320
(2)	Dry to moist sand	0.32, 1.18, 1.19, 1.20, 1.35, 4 (2), 6.21
(3)	Dry to moist sand	27 (6), 36.8 (6), 256 (7)
(4)	Dry clay	255, 320
(5)	Moist clay	1
(6)	Wet clay	64
(7)	Muck	25, 50 (2)
(8)	Moist loess	0.5, 1.0
(9)	Ice	5 (2), 10

In addition, data taken from an experiment (Reference 18) aimed at studying the effect of soil-rock interfaces (Item 3 above) was supposed to be confined to data from shots in which the interface did not influence crater shape (Shots 22 through 30). However, examination shows that two of six 27-pound shots, three of six 36.8-pound shots, and four of seven 256-pound shots had craters which were clearly disturbed by the presence of the interface. More data in a single medium might yield significant departures from the results of these observations.

Considering average values, there is very little departure from cube-root scaling for apparent-crater depth and only a small departure for crater radius, and this may be interpreted as a confirmation of 1/3.4-power scaling. Taken as a whole, then, the information of Table I can be interpreted as a confirmation of either cube-root or 1/3.4-power scaling. The charge weights involved range from fractions of 1 pound to about 310 pounds, with the exception of the 2,560-pound charges used for experiments in sand. Because this range of charges is at the end of the weight scale, yield-dependent departures from cube-root scaling are less likely to appear.

In view of the limitation discussed above, the interpretation made here is that no departures from cube-root scaling are substantiated by these data for surface bursts.

Large HE Charges -- Another interesting set of surface-burst data comes from the surface detonation of hemispherical charges at the Suffield Experimental Station, Ralston, Alberta, Canada (References 19, 20, 21, 22, 23, 24, 25). Since these charges were initiated at the center of the base of the charge, their cratering effectiveness should not be expected to compare precisely with that of a half-buried spherical charge. Nevertheless, the fact that the charges were geometrically similar should provide at least a clue to the scaling.

TABLE I

Surface Burst HE

Soil Type	Number of Observations	Approx. Wt. Range (pounds)	Apparent-Crater Radius	True-Crater Radius	Apparent-Crater Depth	True-Crater Depth
Various	44	0.3-320	$1.54W^{0.32}$		$0.57W^{0.35}$	
Clay	7	0.9-320	$1.87W^{0.27}$		$0.93W^{0.32}$	
Sand	32	0.3-320	$1.67W^{0.30}$		$0.64W^{0.30}$	
Various	18	0.5-320		$1.38W^{0.35}$		$0.71W^{0.31}$
Clay	3	1.0-320		$1.55W^{0.32}$		$0.90W^{0.32}$
Sand	37	25-2560		$1.35W^{0.40}$		
	13	25-320				$1.12W^{0.20}$

Figure 3 shows the results from three experiments involving 10,000-, 40,000-, and 200,000-pound charges; the data are from References 21, 22, and 24. It is interesting to note that both the true- and apparent-crater radii scale as a power of the charge weight larger than 1/3, whereas the true- and apparent-crater depths scale as a power smaller than 1/3. The apparent-crater depth scales as only the 0.17 power of the yield, if only these data are used. The data from References 21, 22, and 24 differ from those of Reference 25 and are considered more accurate. However, if the data from Reference 25 for charges weighing 8, 30, and 500 pounds are included, the apparent-crater depth appears to scale nearly as the fourth-root. (This is indicated in the figure by the dashed line.) The effect of hemispherical charges would differ from that of half-buried spherical charges in that a larger percentage of the energy of the former would go into air blast and consequently a smaller amount into cratering. This explanation may account in whole or in part for the fact that depth is less and radius greater than expected, but since partition of energy is presumably independent of yield, the scaling should be unaffected.

Figure 4 shows that apparent-crater volume is almost directly proportional to charge weight, even though radius scaling is larger than cube-root and depth scaling is less. The best exponent is not readily apparent from the figure, but when the data for 8, 30, and 500-pound charges from Reference 25 are added, it is clear that $V \sim W^{1.05}$. No conclusion can be reached on true-crater volume, since that of the largest charge is an estimate.

These results are different from those of a series of five hemispherical charges, ranging from 1 to 20 tons, burst over coral sand at Elugelab Island, Eniwetok Atoll, in 1952. Crater radii from these tests scaled as the cube-root of the charge

weight. If the detonation point (on which no information is available) was not the same as that of the Suffield experiments, this difference could account for the apparent difference in scaling. Another explanation is the different medium.

Nuclear Charges -- Let us now examine crater data from nuclear surface bursts, including data from Pacific Proving Ground shots. Figure 5 shows crater depth from nuclear surface bursts as a function of yield in kilotons. A least-square fit has been drawn through these data.*

Figure 6, crater radius from nuclear surface bursts plotted as a function of yield, shows that the apparent-crater radius scales as the 0.396 power of charge weight. Note that this agrees well with the scaling of the Suffield high-explosive craters.

Analysis (Reference 11) of surface-burst craters from nuclear shots at the Pacific Proving Ground led in 1957 to the use of cube-root scaling for crater radius and fourth-root scaling for crater depth (Reference 12). Later the fourth-root scaling of crater depth was attributed (Reference 26) to the water washing of the Pacific craters. Let us consider this hypothesis for a moment. If the crater radius is increased by the washing of material from the inner edge of the crater into the crater bottom, thereby decreasing the crater depth, there should be (ignoring differences in density between the pre-washed and post-washed material) a conservation of volume. Figures 5 and 6 suggest that an increase in radius may be obtained at the expense of a decrease in crater depth and also that something approaching

*Data from shots whose yields are still classified were used in determining the least-square fits but are not shown in Figures 5, 6, and 7.

a conservation of crater volume may be involved. Let us assume that the crater is a paraboloid of revolution where

$$V = \frac{\pi d r^2}{2} .$$

Then from Figures 5 and 6,

$$V = \frac{\pi}{2}\left(21.6W^{0.225}\right)\left(60.4W^{0.396}\right)^2 = \frac{247,560W^{1.017}}{2} = 123,780W^{1.017} .$$

Such a line is shown in Figure 7.

But one's intuition is offended by the possibility that crater volume could scale as a power of the yield larger than one. This can be avoided if the crater differs slightly from a paraboloid of revolution, and if the shape changes slowly with yield. The volume could be

$$V = \frac{\pi d r^2}{cw^n} = \frac{247,560W^{1.017 \pm 0.08}}{cw^n}$$

Unfortunately, volume data are insufficient to define adequately the appropriate power of the yield. However, from the few data points for which measured crater volumes are available, a slope appreciably less than 1 can hardly be justified. Clearly an exponent as low as 0.75, which would occur if both linear dimensions scaled as the fourth root of yield, is not indicated by the data.

The craters from large hemispherical HE charges and those from nuclear charges suggest that departures from cube-root scaling, formerly attributed in the latter case to water washing, may be characteristic of surface bursts and that the water washing of Pacific craters may play an insignificant role.

CRATERS FROM SUBSURFACE BURSTS

Small HE Charges -- WES also obtained least-square fits (Reference 17) to crater data from charges fired below the surface, in a variety of soils. The results are summarized in Table II. Here, with one exception, departures from cube-root scaling seem to be evident. Still, the inclusion of a variety of soil types casts doubt on the validity of the specific exponents derived. Relatively soft and weak soils such as loess were used at the lower yield range, while hard, strong soils such as Dugway dry clay were used at the upper yield range; the net effect should produce a power less than one-third.

TABLE II

Subsurface Burst HE

Soil Type	Number of Observations	Approx. Wt. Range (pounds)	Scaled Burst-Depth Range ($ft/lb^{1/3}$)	Apparent-Crater Radius	Apparent-Crater Depth
Various	207	0.3-320,000	0-1		$101W^{0.31}$
	240	0.3-320,000	0-1	$2.15W^{0.31}$	
	64	0.12- 3,200	1-2		$1.01W^{0.34}$
	175	0.12- 3,200	1-2	$2.70W^{0.30}$	

The WES analysis represents an attempt to fit with a single power, arrived at statistically, a function which, if overburden approximate scaling is correct, must have a power changing from 1/3 for charges weighing about one pound to something less than 1/3 for very large charges. But while they arrived at powers smaller than 1/3, it is not possible to separate the effect of scaling from the effect of having mixed data from a variety of media.

It is the thesis here that cube-root scaling obtains for all charges of about one pound, since in this area the effects

of gravity (i.e., the overburden) are certainly too small to cause significant departures.

Large HE Charges -- The analysis of the larger HE subsurface charges has certainly confirmed a departure from cube-root scaling for NTS desert alluvium. That departure has been characterized as a single fractional power (less than 1/3) of charge weight (References 8, 9, 10) and as an equivalent to a fractional power varying from 1/3 for small charges or surface bursts to 1/4 for very large deeply-buried charges (Reference 13). Overburden approximate scaling indicates cube-root scaling for surface bursts, but this not only conflicts with experimentally derived values but also does not define precisely the peak of the scaled depth-of-burst curve. Nonetheless, it is especially attractive because it provides a means of scaling from one pound to one million pounds, from cube-root to fourth-root, in a manner consistent with experimental data.

Nuclear Charges -- The scaling of craters from subsurface nuclear bursts at near optimum depths is based primarily on the results of Project Sedan, although Teapot Ess at a much shallower depth and Jangle U at a still shallower depth contribute somewhat to the interpretation. The scaling appropriate depends on whether one assumes that there is or is not a difference in cratering effectiveness between nuclear and chemical explosives; however, this depends in turn on the method of scaling assumed. This question will therefore remain open until two shots of equal yield, one nuclear and the other high-explosive, are fired in the same medium at the same near-optimum depth.

The interpretation chosen here is that differences in efficiency do exist but that they are small, and that Sedan indicates fourth-root scaling for yields over one kiloton at optimum burst depths.

DEPTH-OF-BURST CURVES FOR NUCLEAR EXPLOSIVES

One Kiloton -- Crater radius and crater depth scaled to one kiloton by cube-root scaling are shown in Figures 8 and 9, respectively, and scaled to one kiloton by fourth-root scaling, in Figures 10 and 11, respectively. When the data for surface and near-surface bursts at the Pacific Proving Ground are included, the tendency is for fourth-root scaling to cause a greater dispersion of the crater radius data than cube-root scaling. Fourth-root scaling, however, causes a smaller dispersion of crater depth data than cube-root scaling. These observations are consistent with those of the preceding section. In constructing the curves through the data points, considerable emphasis was placed on the craters from the Small Boy, Jangle S, Jangle U, Johnie Boy, and Teapot Ess shots, because they involve more nearly comparable media. By concentrating on data from shots whose yields were approximately one kiloton, it has been possible to construct one-kiloton depth-of-burst curves for which, over the region of interest, the method of scaling is not of very great importance.

One Megaton -- In preparing depth-of-burst curves for one megaton, however, a method of scaling must be chosen. Overburden approximate scaling has been taken as a guide in the selection of a scaling method, since over the yield range from one kiloton to one megaton it is not in significant disagreement with fourth-root scaling at the deeper burst depths. Fourth-root scaling has therefore been assumed for the deeper burst depths over the one-kiloton to one-megaton range. Heavy reliance has been placed on the Sedan data.

Since craters from surface bursts in the Pacific have volumes directly proportional to yield, radii proportional to greater than the 1/3 power, and depths proportional to less than the 1/3 power, one must ask to what extent this is due to water

washing. As discussed earlier the interpretation given here is that water washing accounts for little, if any, of the departure from cube-root scaling. Another question is whether one is justified in applying the Pacific results ($d \sim W^{0.225}$, $r \sim W^{0.396}$) to surface bursts in Nevada desert alluvium. In favor of the application are the Suffield data which show that for an unwashed soil $d \sim W^{0.26}$ and $r \sim W^{0.41}$, an even more extreme departure from $W^{1/3}$ than the Pacific results. However, the fact that in the Suffield experiments hemispherical rather than spherical charges were used detracts much from this argument. It can be argued that even though departures from cube-root scaling in alluvium exist, they may be different from those in the Pacific coral medium, and that since there is no way of evaluating the departures for alluvium, one has no alternative but to accept straight cube-root scaling. This course seems the less desirable, since it ignores experimental information entirely.

Basing the argument that water washing accounts for little, if any, of the departure from cube-root scaling on volume alone strengthens it very little. Presumably, $V \sim W^p$. The following three situations can influence p. (1) When material washes from the sides of the crater into the bottom of the crater, the shape is changed but the volume is not. Since the volumes of a washed and an unwashed crater are the same, it can be concluded that the exponent p is the same in both cases. (2) When in situ material washes from the side of the crater into the bottom it can be presumed to decrease in density. If we assume that the in situ material involved represents the same percentage of the crater volume for all yields, then the volume of the washed crater is less than that of the unwashed crater. However, the exponent p is not affected; it remains the same for both washed and unwashed craters. (3) Material thrown out of the crater onto the crater lip is also washed back into the crater, with the result that the volume of the washed crater is smaller than that of the

unwashed crater. **Since the distance material is ejected depends on yield, the percentage which washes back may also be yield** dependent. We may assume three cases: **(a) Less throwout material** (a smaller percentage of the total) **is washed back into** the crater as the yield is increased, **in which case p is larger** for a washed crater than for an unwashed crater. **(b) The same** percentage of the throwout material is washed back **regardless** of yield, in which case p is the same for washed and **unwashed** craters. (c) More throwout material (a **larger percentage of** the total) is washed back into the crater as **yield is increased,** in which case p is smaller for a washed **crater than for an un**washed crater.

If crater radius and depth both scale as **the cube root** of yield, p = 1; if they scale as the **fourth root, p = 3/4; and** if they scale differently, p is same **function of both. The ob**served value for the Pacific craters was **p = 1, and only two** combinations of the above considerations **can give p = 1:**

(1) Volume is proportional to yield ($p = 1$), **and water** washing does not influence scaling because **the per**centage of throwout which washes back **remains con**stant for all yields. **(Situations 1, 2, 3-b).**

(2) Some scaling ($p < 1$) **applies but is exactly offset** by a **smaller percentage of material being washed** back into **the crater as yield is increaed, so that** the observed result is $p = 1$.

If for surface bursts $V \sim W$ and for bursts **at near optimum** burst depths $V \sim W^{0.75}$, **there is the apparent paradox that extra**polation predicts a yield **beyond which a larger crater results** from a surface burst than **from the same yield at optimum depth.** For a 1-kiloton surface burst, $V = 1.43 \times 10^5$ **W in cu. ft. For a** 1-kiloton burst near optimum, $V = 5.3 \times 10^6 W^{0.75}$. **The volumes for** surface and optimum depth bursts become equal at about 2,000

megatons. This yield is nearly 200 times larger than our largest Pacific datum, and long before it is reached a change in the relative importance of crater mechanisms could prevent the surface burst from becoming the larger of the two.

The same argument may be extended to crater radius. (There is no apparent conflict in crater depth since Pacific data indicate that $d \sim W^{0.225}$ (essentially $W^{0.25}$) for surface bursts and $d \sim W^{0.25}$ for optimum burst depths.) The Pacific data indicate that $r \sim 66.8\, W^{0.395}$ for surface bursts and $r = 180\, W^{0.25}$ for optimum bursts. If differences in media are ignored, the radii of surface and optimum-burst-depth shots become equal when the yield is about 1.2 megatons.

Figure 12 is the crater depth versus burst depth curve of Figure 11 scaled to one megaton by fourth-root scaling, and Figure 13 is the radius curve of Figure 8 scaled to one megaton by fourth-root scaling (line A). Line A gives the minimum possible crater dimensions with emphasis placed on the crater of Teapot Ess. Line B gives emphasis to Jangle Underground, in which there is less confidence. The best curve undoubtedly lies between the two. The above-ground portions of curves A-B have been scaled by fourth-root scaling, even though at some height of burst the crater dimension must relate only to air blast which scales as the cube root. However, the transition from cube root to fourth root is an uncertainty.

There is some evidence that for a surface burst crater radius scales as a power greater than 1/3 while for deeper bursts (such as Sedan, the upper right datum) it scales as the 1/4 power. If surface bursts scale exactly as the 1/3 power, the curve would cross the zero depth axis as does line C. The transition from that point (line C with the zero burst depth axis) to curve B is uncertain. The above-ground portion has been scaled as the cube root. The best curve for this portion would be the cube-root

curve for the higher burst height with a transition to fourth-root scaling at some unspecified depth.

Radii of craters from surface bursts at the Pacific Proving Ground have suggested that the scaling for crater radius may be as large as $W^{0.4}$. The 0.4 power would then apply at the surface and the 1/4 power at the scaled depth of Sedan, with a transition occurring in some uncertain manner between the two. Line D, which arbitrarily connects the zero burst depth axis and the Sedan datum, gives an upper limit on crater radius.

The above-ground portion of the curve has also been scaled as the 0.4 power, again suggesting an upper limit. As in the preceding case, cube-root scaling probably is best at the higher burst heights, with a transition to $W^{0.4}$ occurring in an uncertain manner.

These curves are especially useful in emphasizing the uncertainties which result from a lack of knowledge of crater mechanisms and from the absence of an adequate scaling law.

SUMMARY

Table III summarizes the scaling for crater radius, depth, and volume for bursts at the surface and at near optimum burst depth. The letters in parentheses refer to the summary below the table.

TABLE III

	From 1 to 10 lb	From 1 to 1000 kt
Surface		
Radius	$W^{1/3}$ (a)	$W^{0.4}$ (b)
Depth	$W^{1/3}$ (a)	$W^{1/4}$ (b)
Volume	W (a)	W (c)
Near Optimum Depth		
Radius	$W^{1/3}$ (a)	$W^{1/4}$ (d)
Depth	$W^{1/3}$ (a)	$W^{1/4}$ (d)
Volume	W (a)	$W^{0.75}$ (d)

(Charge weights falling in the region between the two columns scale in an intermediate manner which cannot now be specified for surface bursts but is best described by overburden approximate scaling for bursts near the optimum depth of burst.)

a. Gravity (overburden) effects which appear to affect crater scaling are too small for very small charges to produce observable departures from cube-root scaling even at optimum burst depths. The small surface charge cratering analysis done by WES could be interpreted in part as a departure from cube-root scaling. However, the wide limits within which the data fall, the moderately small yield range covered, and the mixture of dense soil data at upper yield range with data from less dense soils at the smaller yields make less convincing the argument that these data show a departure from cube-root scaling. The use of a single fractional-power exponent less than 1/3 to describe scaling over a wide range of charge weights may be

only approximate scaling, as indicated by the overburden approximate method, in which cube-root scaling for small charges slides to fourth-root scaling for very large charges.

b. Data from nuclear surface bursts at the Pacific Proving Ground and Suffield large HE surface bursts show crater radius scaling as a power of yield larger than 1/3 and depth as a smaller power. The trend suggested by these two groups of data is expected to hold for desert alluvium, but there is no reason to expect the applicable value to be precisely the same as the nuclear-Pacific values or the HE - Suffield (hemispherical charge) values. It seems preferable to assume the values from the Pacific data than to fall back on the cube-root scaling indicated by overburden approximate scaling.

c. Experimental data indicate that the volumes of craters from surface bursts are directly proportional to yield.

d. Overburden approximate scaling suggests fourth-root scaling, and the interpretation of the Sedan data chosen here substantiates this. Another interpretation is that nuclear craters are sufficiently smaller than high-explosive craters to allow 1/3.4-power scaling to continue to obtain. For bursts at near optimum depth, overburden approximate scaling is especially convenient because it provides the means for transition from cube-root to fourth-root scaling between small and large charge weights.

If the scaling for surface bursts developed here from the experimental data turns out to be correct, an explanation for it must be sought in cratering mechanics rather than in simple dimensional considerations.

RECOMMENDATIONS

This analysis has clearly and emphatically pointed up the need for nuclear and chemical cratering explosions made under identical conditions for the purpose of defining the relative cratering effectiveness of nuclear and high-explosives.

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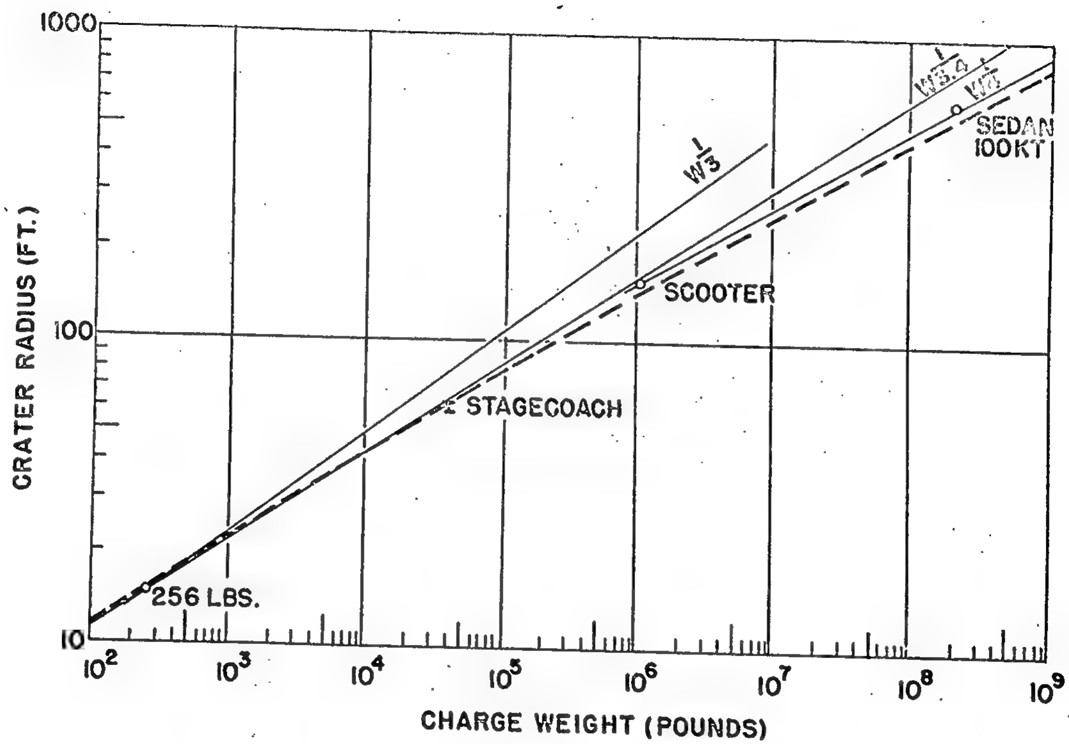
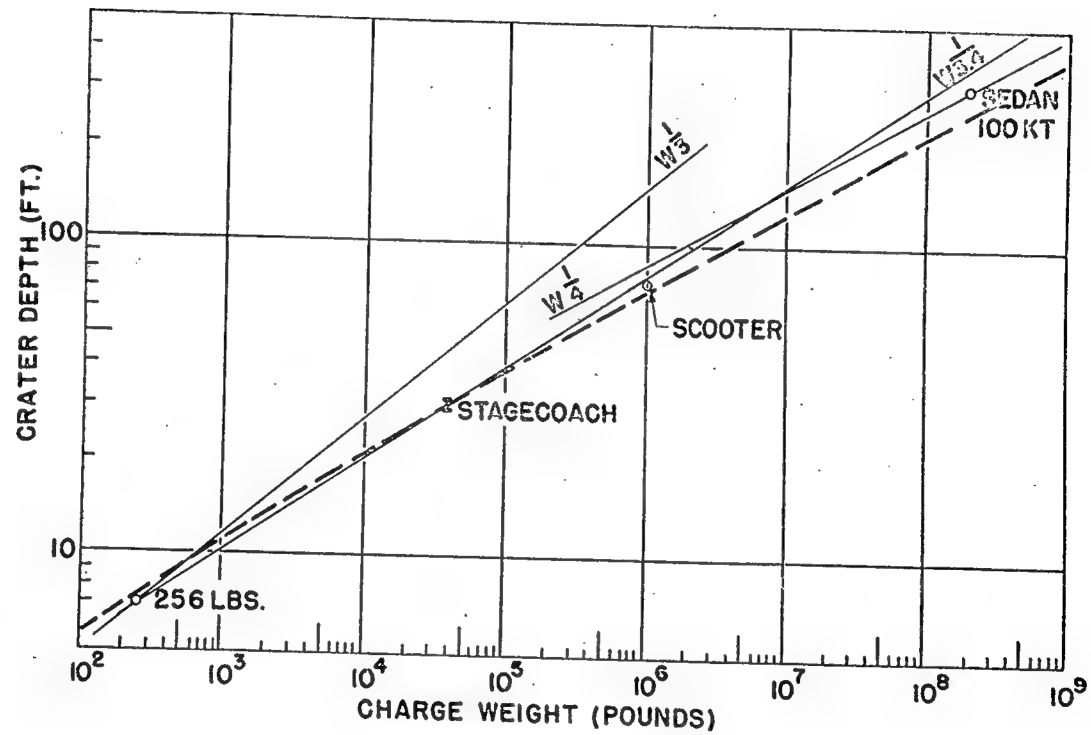
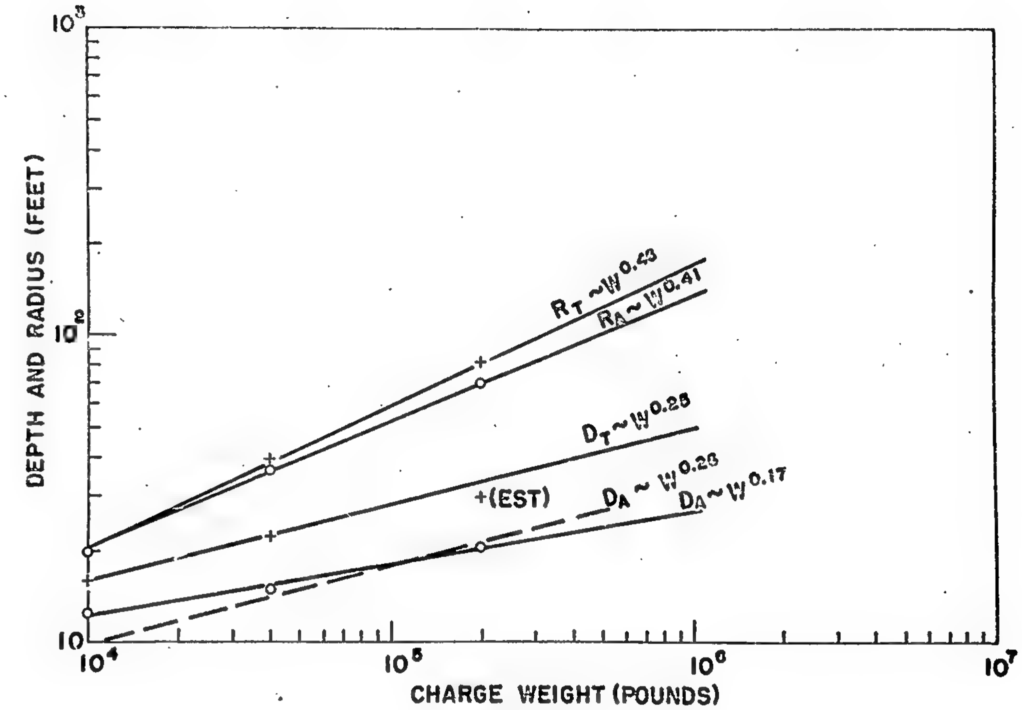
LIST OF FIGURES



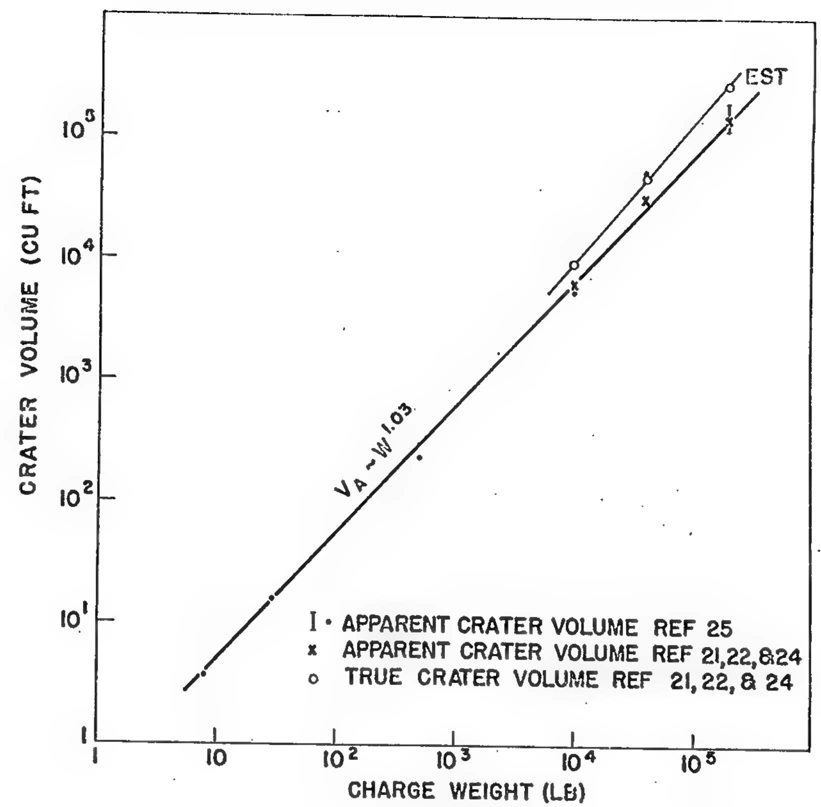
1000
100
10
CRATER RADIUS (FT.)
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
CHARGE WEIGHT (POUNDS)
$\frac{1}{W3}$
$\frac{1}{W3.4}$
SEDAN
100KT
SCOOTER
STAGECOACH
256 LBS.



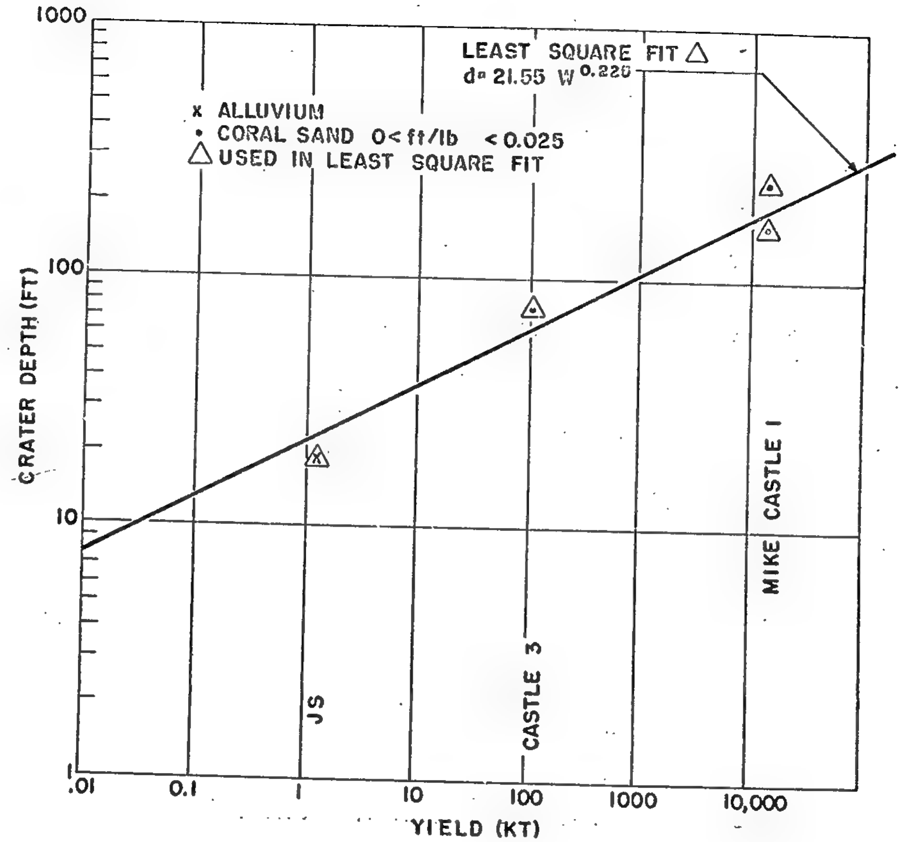
CRATER DEPTH (FT.)
100
10
$W^{\frac{1}{3}}$
$W^{\frac{1}{4}}$
$W^{\frac{1}{3.4}}$
SEDAN
100 KT
SCOOTER
STAGECOACH
256 LBS.
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
CHARGE WEIGHT (POUNDS)

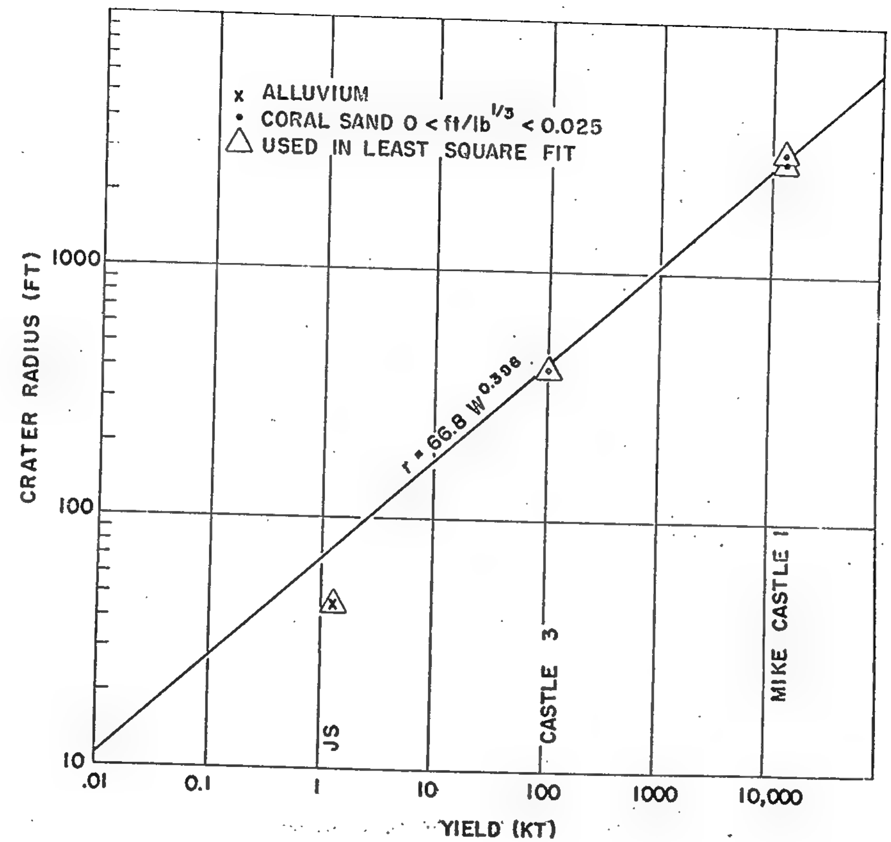


DEPTH AND RADIUS (FEET)
CHARGE WEIGHT (POUNDS)
$R_T \sim W^{0.43}$
$R_A \sim W^{0.41}$
$D_T \sim W^{0.25}$
+(EST)
$D_A \sim W^{0.23}$
$D_A \sim W^{0.17}$

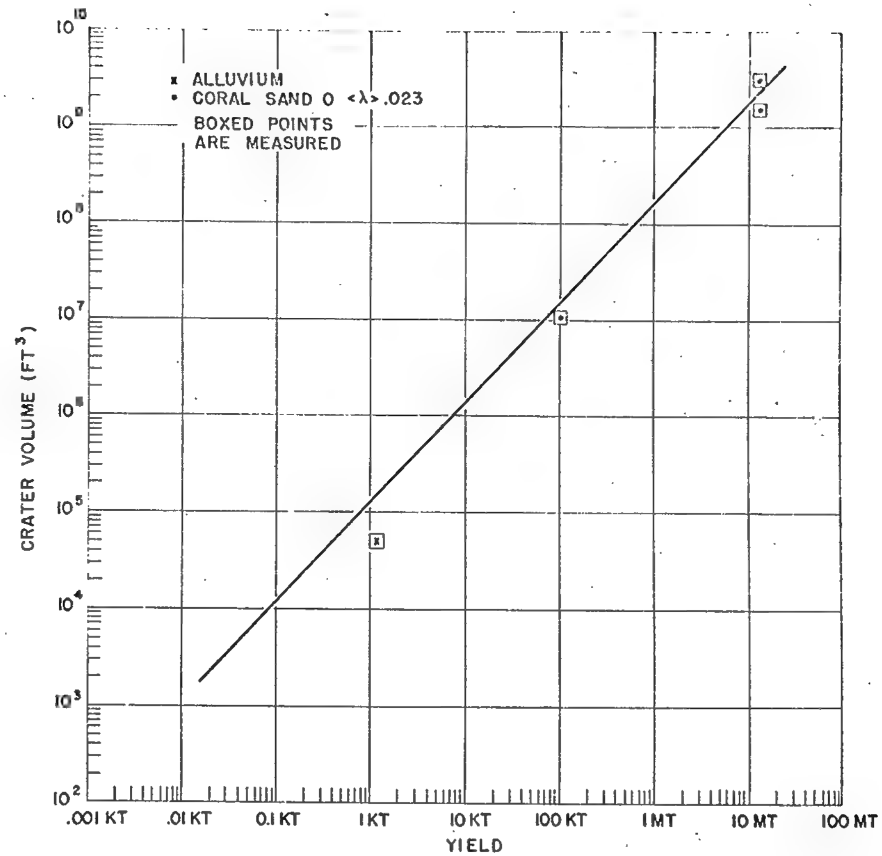


EST
$V_A \sim W^{1.03}$
I • APPARENT CRATER VOLUME REF 25
x APPARENT CRATER VOLUME REF 21,22,&24
o TRUE CRATER VOLUME REF 21, 22, & 24
CRATER VOLUME (CU FT)
CHARGE WEIGHT (LB)

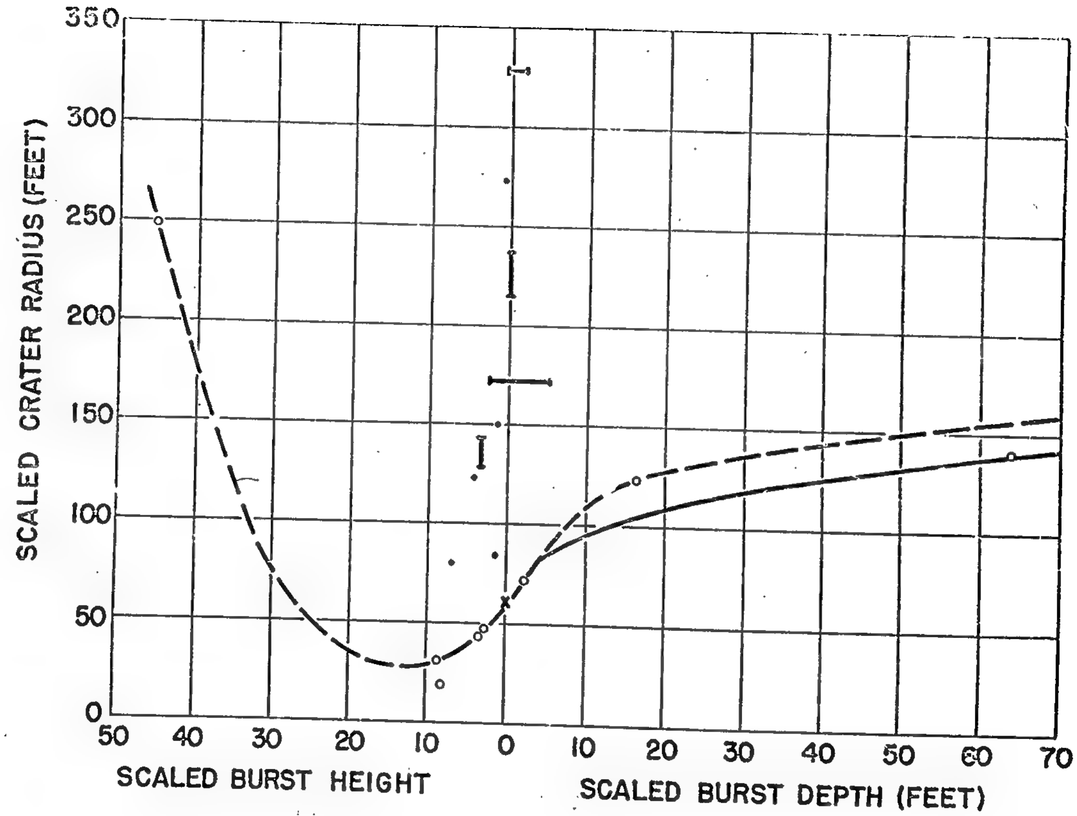

LEAST SQUARE FIT △
d= 21.55 W 0.220
x ALLUVIUM
• CORAL SAND 0< ft/lb < 0.025
△ USED IN LEAST SQUARE FIT
MIKE
CASTLE I
CASTLE 3
JS
CRATER DEPTH (FT)
1000
100
10
1
.01
0.1
1
10
100
1000
10,000
YIELD (KT)

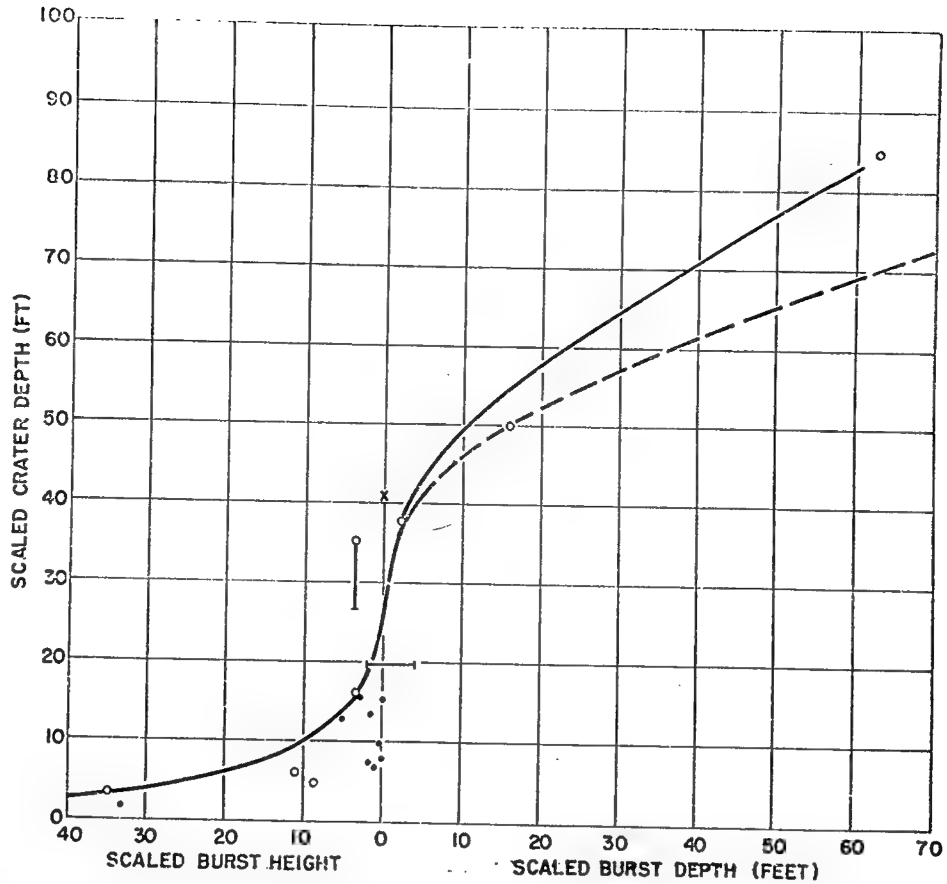


x ALLUVIUM
• CORAL SAND 0 < ft/lb^1/3 < 0.025
△ USED IN LEAST SQUARE FIT
r = 66.8 W^0.306
JS
CASTLE 3
MIKE CASTLE 1
CRATER RADIUS (FT)
10
100
1000
.01
0.1
1
10
100
1000
10,000
YIELD (KT)

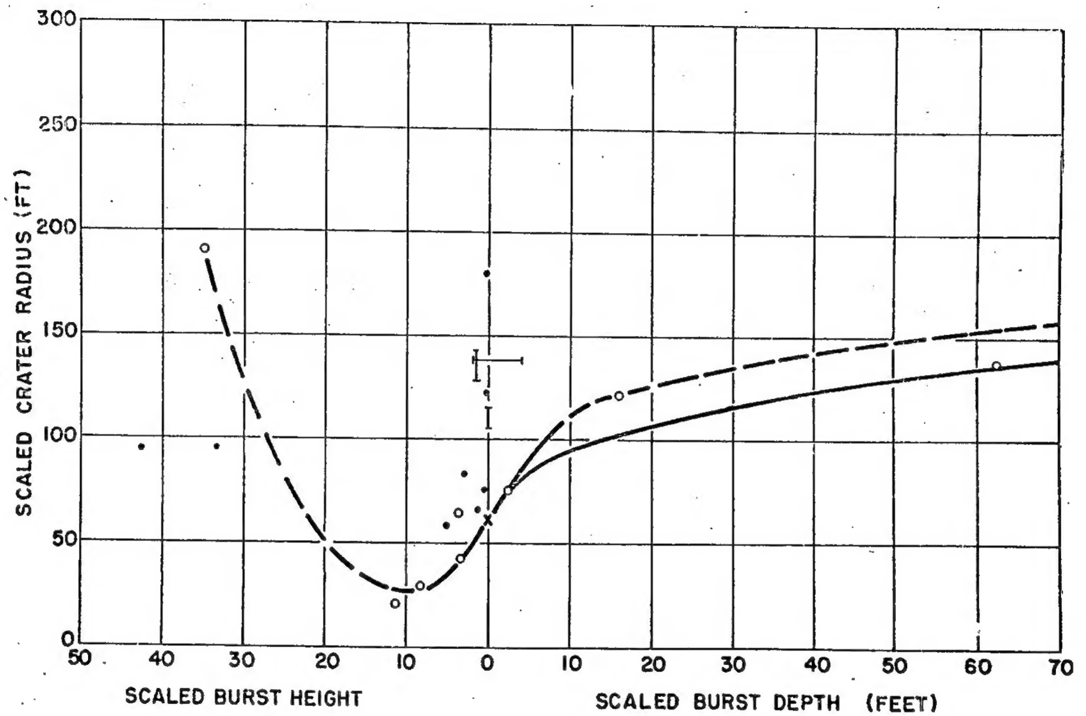


x ALLUVIUM
• CORAL SAND 0 <λ> .023
BOXED POINTS
ARE MEASURED
CRATER VOLUME (FT³)
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
.001 KT
.01 KT
0.1 KT
1 KT
10 KT
100 KT
1 MT
10 MT
100 MT
YIELD

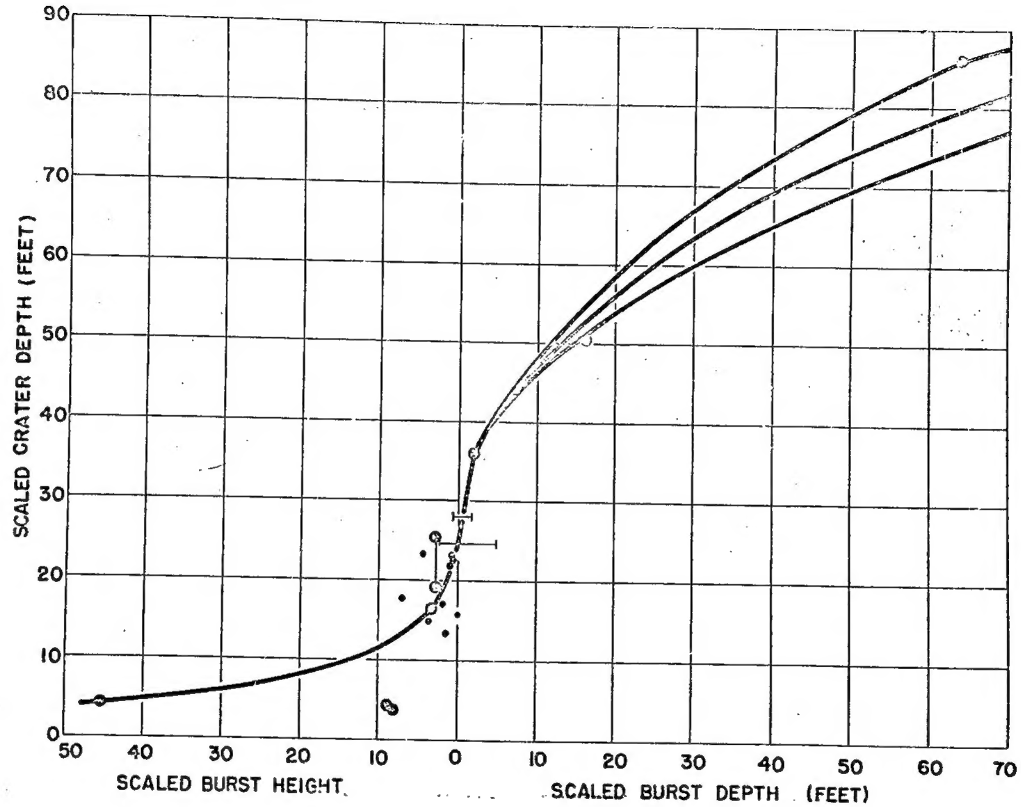

SCALED CRATER RADIUS (FEET)
SCALED BURST HEIGHT
SCALED BURST DEPTH (FEET)



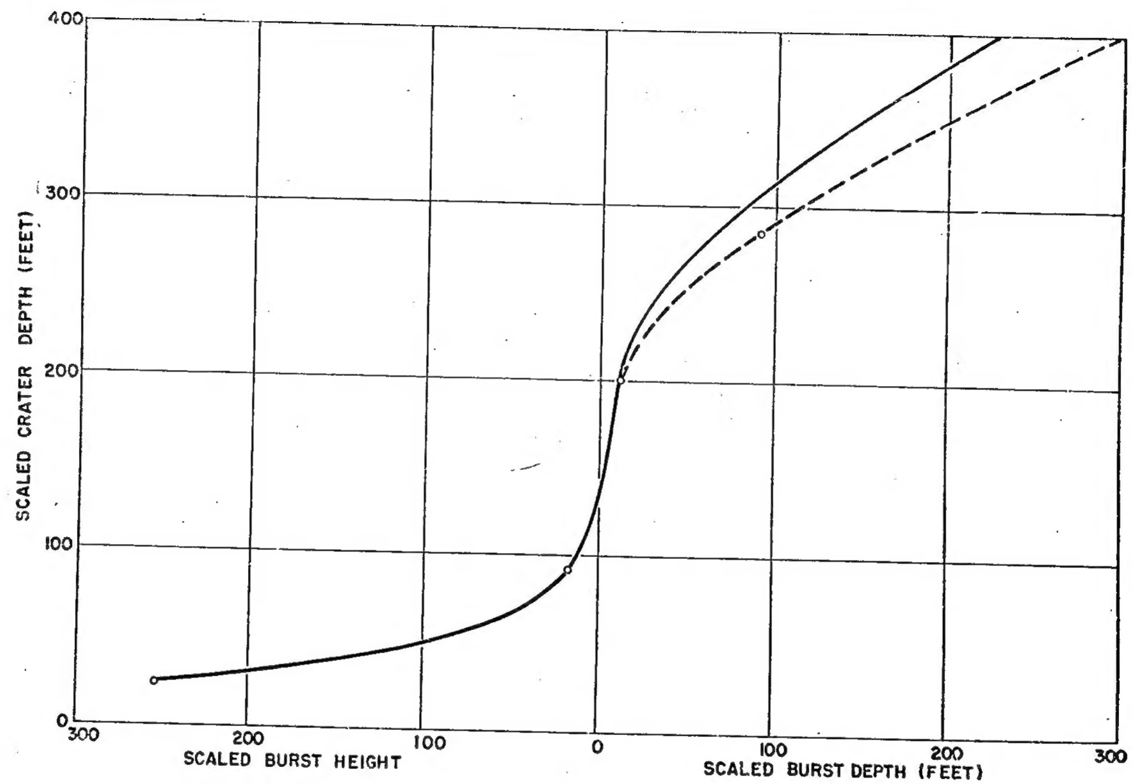
SCALED CRATER DEPTH (FT)
100
90
80
70
60
50
40
30
20
10
0
40
30
20
10
0
10
20
30
40
50
60
70
SCALED BURST HEIGHT
SCALED BURST DEPTH (FEET)



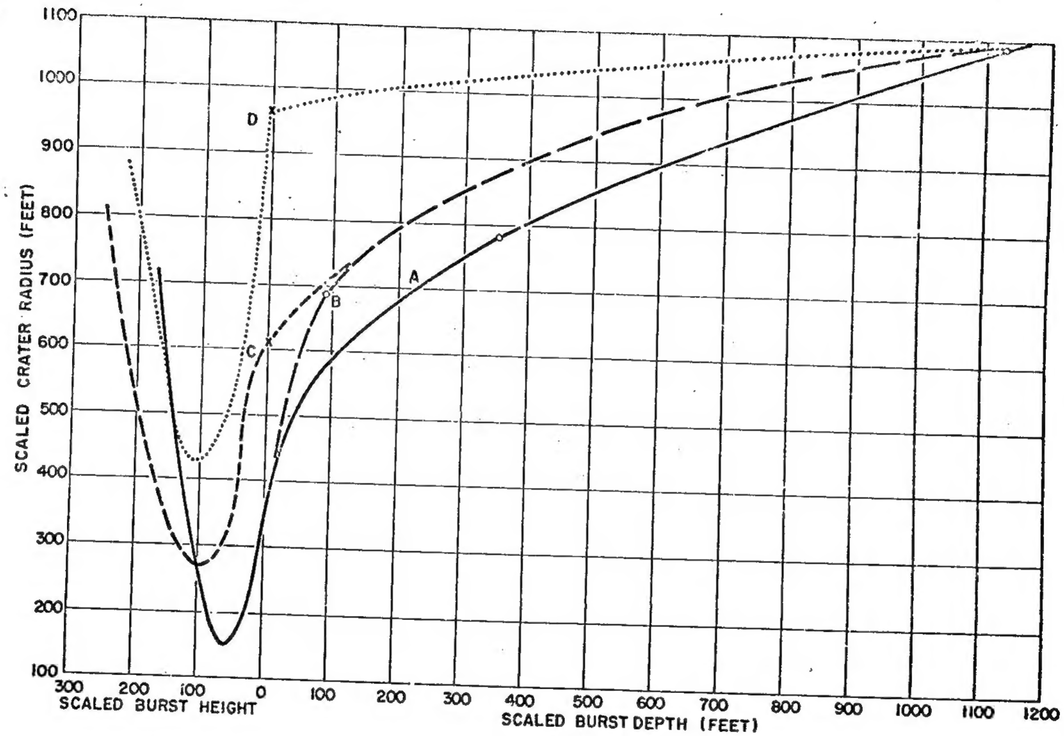
SCALED CRATER RADIUS (FT)
300
250
200
150
100
50
0
50
40
30
20
10
0
10
20
30
40
50
60
70
SCALED BURST HEIGHT
SCALED BURST DEPTH (FEET)



SCALED CRATER DEPTH (FEET)
90
80
70
60
50
40
30
20
10
0
50
40
30
20
10
0
10
20
30
40
50
60
70
SCALED BURST HEIGHT
SCALED BURST DEPTH (FEET)



SCALED CRATER DEPTH (FEET)
400
300
200
100
0
300
200
100
0
100
200
300
SCALED BURST HEIGHT
SCALED BURST DEPTH (FEET)


SCALED CRATER RADIUS (FEET)
1100
1000
900
800
700
600
500
400
300
200
100
300
200
100
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
SCALED BURST HEIGHT
SCALED BURST DEPTH (FEET)
A
B
C
D

END